Using Optical Communications Links for Deep-Space Navigation

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***Abstract*—Optical communications systems that are being developed for deep-space missions could also be used to perform deep-space navigation. A two-way optical communications system could be modified to support ranging, and the laser signal emitted by a spacecraft could be tracked against background stars to perform plane-of-sky observables. We have been analyzing a number of deep-space navigation scenarios to understand the advantages and disadvantages of using optical communication systems for navigation. Our objectives were to evaluate the performance achievable with optical systems, and to study under what circumstances these systems could be sufficient to navigate the mission, reducing the requirements for radio systems to perhaps just to be a backup for emergency communications.**

Keywords—navigation, orbit determination, optical tracking

I. Introduction

Since the beginning of interplanetary spaceflights, radio communication systems have been the main means of providing the tracking data necessary to navigate deep space missions to their intended destinations. Optical communication links could allow for much increased data rates from deep-space probes. Thus, transitioning interplanetary communications from radio to optical frequencies could lead to increasing data rates by several orders of magnitude [1]. NASA is currently developing laser communication systems to allow much higher volumes of scientific data to be transmitted to Earth from deep space. JPL's first generation deep space optical communications terminal, which is planned to fly in an upcoming Discovery mission, has a primary focus on communications, as is appropriate for an initial technical demonstration. In the future, optical communications infrastructure could be solely used for both navigation and data transmission. It could also significantly reduce spacecraft mass and power allocations by eliminating requirement for a separate on-board radio-frequency tracking system.

A number of missions have tested the use of lasers at deep-space distances. Some of these tests have demonstrated that optical links could be used to perform tracking that could help navigate interplanetary probes. The use of deep-space optical telecommunication links for interplanetary navigation has been proposed before. It was analyzed as part of an earlier proposal for a deep-space optical communications system [2] and was also discussed in a more recent monograph published by DESCANSO [1]. The Galileo mission showed that ground-based lasers could be detected by a spacecraft camera from space [1]. Deep-space laser ranging experiments have been carried out with the Mercury Laser Altimeter in Messenger [3,4] and with the Lunar Orbiter Laser Altimeter carried by the Lunar Reconnaissance Orbiter [5], but those systems were not designed to provide optical tracking capabilities sufficient to replace the radio-frequency tracking systems.

Optical navigation data types would include ranging between spacecraft and a ground station on Earth, as well as high-precision astrometric measurements of angular positions—with optical telescopes on Earth (and in space)—that will be made much more precise by the high-precision optical celestial reference frame being obtained by ESA's Gaia mission [6]. The development of these new optical navigation data types, as well as the required tie between the optical and radio celestial references frames, will also open new opportunities for innovative science investigations, not only similar to the science benefits reaped from the development of radio navigation techniques, but also opening new opportunities.

Our objective is twofold: to investigate the navigation performance that could be achieved with the use of the envisioned optical communications infrastructure and also to assess mission scenarios where adequate navigation performance can be achieved. The goal is to determine the conditions under which a mission carrying an optical communications terminal need not also carry a second radio frequency transponder—thereby saving mass, power, and cost—thereby reducing the complexity of the spacecraft and mission operations. To do that, we used JPL's operational navigation software, the Mission analysis and Operation Navigation Toolkit Environment (MONTE) [7], developing a set of simulations to assess optical navigation performance,

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relying on realistic estimates for the performance of future on-board and ground-based optical terminals. We analyzed a number of missions, with different navigation requirements, to understand under what conditions optical navigation performance would be sufficient to fulfil mission requirements. In Section II, we describe the current architecture for deep space optical communications; in Section III, we describe the potential "optimetrics," the quantities equivalent to those measured with radio frequencies that could be measured by optical communications infrastructure, and in Section IV, we consider specific use cases.

II. Deep-space Optical Communications

Future human and robotic NASA missions may need to communicate at data rates much higher than those feasible with current radio frequency systems. One promising way of substantially increasing data rates would be to move from the radio bandwidth of the spectrum to the optical band. Optical communications systems could work at data rates up to 100 times higher than comparable radio systems of similar mass, volume, and power consumption. NASA is preparing and performing technology demonstration missions to showcase optical communications in space [8]. The Lunar Atmosphere and Dust Environment Mission (LADEE) mission carried out the Lunar Laser Communication Demonstration that achieved data rates of up to 622 Mbps at Moon-to-Earth distances, and also performed time-of-flight measurements with errors at the few centimeter level [9]. In the near future, the Laser Communications Relay Demonstration will showcase data transmission between the Earth and near-space, but during its two-year mission will also provide valuable experience on the operation of the ground optical stations [10]. The next planned step would be the demonstration of deep-space optical communications when the Deep Space Optical Communications (DSOC) terminal [11] is due to be flown on the NASA's Psyche mission (funded under NASA's Discovery program), which currently is scheduled for launch in 2022. While the DSOC terminal does not currently have the capability to perform time-of-flight measurements, it should be able to demonstrate ground-based astrometric tracking.

System analyses of deep-space optical communications systems have shown that data rates from 5 to 40 Mbps are possible for a reasonably sized system transmitting from Mars orbit [12]. In the case studied, a 30-cm diameter flight telescope with a 5 W transmitted power was baselined, together with a 10-m diameter ground receive antenna.

For a two-way communications system, the three elements that need to exist are the ground uplink terminal, the flight terminal, and the ground downlink terminal. As it is the case for radio, deep-space optical communications systems will be asymmetric, with the ground components of a larger size and able to transmit at a higher power level than the flight components. These elements will be outlined in the following paragraphs.

A. *Ground Laser Transmitter*

A deep-space optical uplink terminal is equipped with a high-power laser, needed to facilitate the acquisition of the signal by the flight terminal. The uplink system can be used to transmit data to the spacecraft; it could also be used as a beacon to provide pointing reference for the flight terminal. Since the round-trip light times involved in deep-space communications are large, the ground will need to be able to point ahead to the predicted position of the flight terminal; using a closed-loop scanning method that requires confirmation of acquisition by the flight terminal would not be practical in this scenario. There may be cases, as for a spacecraft orbiting a solar system body, for which the ground cannot continuously track the spacecraft signal as it transmits, as the spacecraft may appear occulted by the body at the time that the signal transmitted from the ground terminal. In addition, the system needs to comply with FAA and USSTRATCOM regulations in order to ensure the safety of aircraft, and to protect sensitive space assets. For the DSOC technology demonstration, the Optical Communication Telescope Laboratory (OCTL) at the Table Mountain Observatory, a 1-m telescope, is being equipped with a 5 KW laser and the associated control and monitoring equipment to ensure safe and precise operation.

Fig. 1. The OCTL telescope at the Table Mountain Observatory (NASA/JPL-Caltech)

B. *Deep Space Optical Flight Terminal*

The flight terminal proposed for DSOC is equipped with a 22-cm telescope and a 4-W laser. The telescope can point up to 3 degrees off the Sun. The mass of the entire system is less than

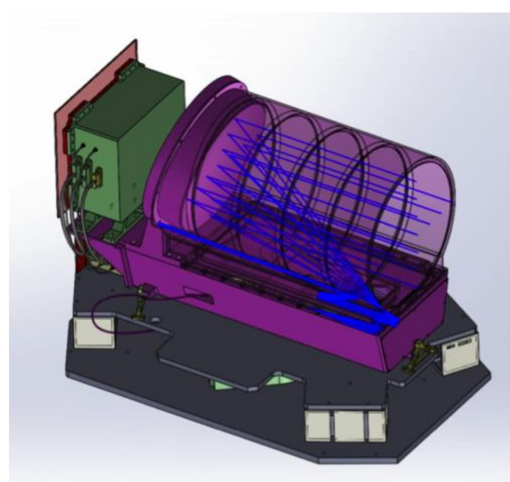

Fig. 2. CAD model of the DSOC Flight Terminal [11] (NASA/JPL-Caltech)

38 kg, requiring less than 100 W to operate. The terminal receives in the 1064 nm band and transmits in the 1550 nm band, relaying on reflective optical systems with an off-axis Gregorian telescope design. The terminal needs to precisely point in order to receive and, especially, transmit, using the ground beacon to adjust pointing. The transmit boresight needs to be offset with respect to the receive boresight to account for the possible separation of the ground transmit and receive stations, and for the motion of the stations during the light-time. The terminal will have the capability to model the trajectory of the spacecraft and of its position relative to the Earth in order to be able to point precisely [11].

C. *Ground Laser Receiver*

For the DSOC demonstration, the Palomar 5-meter Hale telescope will be used as the optical receiver, by installing a superconducting nanowire photon counting detector at its coudé focus. The telescope will be limited to point no closer than 12 degrees from the Sun during the demonstration mission, but future operational optical receivers, after being properly configured, should be able to operate at smaller angles [13].

Fig. 3. The Hale telescope at the Palomar Observatory (Caltech/Palomar Observatory)

III. Deep-space Optical Tracking

Deep space optical communication links can be used or adapted to provide measurements of the position of the spacecraft. Without modifying the flight terminal, the laser signal emitted by the spacecraft can be tracked by an imaging telescope against the position of nearby stars to determine the plane-of-sky position of the spacecraft relative to the ground station. The link can also be used to measure the time of flight between two terminals, but this may require upgrades to ensure precise timing of the transmitted and received signals.

Optical tracking would be affected by the same limitations as optical communications, e.g. a system with just one ground station would not provide the same availability as a radio station. Setting up a network of multiple sites with uncorrelated weather could achieve availability numbers that will fulfil the current Deep Space Network requirement, while allowing for higher data volumes—even when taking into account weather—than those supported by a similar number of radio antennas [14].

One clear limitation of optical links is that they require precise pointing of the telescopes and lasers involved. While spacecraft radio systems can use omnidirectional low-gain-antennas and still close the loop over interplanetary distances, such an optical system is not possible. That may limit the usability of optical systems and force missions to also carry a low-performance radio system to be used in case of emergencies, or to communicate and track while the spacecraft is not able to point the optical terminal to the ground.

A. *Ground-based Spacecraft Astrometry*

Laser beams transmitted by spacecraft can be tracked against the star background to determine the angular position of the spacecraft with respect to the observer in the inertial reference frame [15]. The detector design required for astrometric imaging applications is different (i.e., large format, fast and low noise read-out) compared to that needed for communications or ranging (which require counting and time-tagging photons).

The current state-of-the-art method for determining the plane-of-sky position of spacecraft is with delta-differential one-way ranging (ΔDOR) measurements, but this radio-frequency method requires common visibility of the spacecraft from two widely separated ground antennas, with each measurement only observing one of the dimensions of the plane-of-sky position of the spacecraft. This method is being used for cruise and approach navigation of missions to different bodies of the solar system and can achieve an accuracy at the 1 nanoradian level [16]. The achievement of a similar accuracy using optical systems presents a number of challenges: the position of the reference starts have to be known to that accuracy; the movement of the spacecraft with respect to the field of view has to be modeled; and atmospheric perturbations have to be reduced or compensated.

The Gaia mission is in the process of obtaining a highly-precise catalog of optical sources that will enable optical source position to an accuracy of 0.3 mas for the 2 million brighter stars. Gaia is also observing distant galaxies that contain strong radio sources, quasars, which have been accurately positioned using radio VLBI. An effort is underway to align the radio frame that has been used up to now for solar system ephemeris estimation and interplanetary navigation with the optical frame implicit in the Gaia catalog [17]. The resultant dense set of optical sources will allow for the use of a narrow field of view, reducing the effects of atmospheric turbulence and differential refraction, and also will facilitate determination of the field distortion of the optical detector [15].

A spacecraft operating in deep space, be it in interplanetary space of in proximity to a solar system body, will move with respect to the star background. The motion can be modeled using the a priori knowledge of the orbit of the probe, and a series of short-exposure observations will be combined to minimize streaking, the effects of atmospheric turbulence, and of non-uniform pixel response, synthetically tracking the spacecraft as it moves across the sky. These techniques are currently being explored by performing observations of asteroids, since there are no deep-space spacecraft carrying a laser currently in operation [15].

Error budget calculations show that, under good observing conditions, it may be possible to resolve the position of the spacecraft to about 1 nanoradian using a telescope with a diameter of 5 meters or wider, and to 5 nanoradians when using a 1-meter telescope, with integration times on the order of one hour [15]. This accuracy assumes a dark and clear sky, and an observing elevation within 30 degrees of zenith. While ΔDOR is possible day and night, and it is not very sensitive to atmospheric conditions, precise optical astrometry will only be possible at night and with clear skies. That will mean that this type of measurements will not be possible for small Sun-Earth-probe angles. In the other hand, while ΔDOR is only possible during the short periods of overlap between two distant ground complexes, optical astrometry could be conducted over longer observing sessions.

B. Deep-space Optical Ranging

The possibility of using optical systems for line-of-sight measurements has been analyzed since deep-space communications system were first proposed [18]. A high-data rate optical link could be adapted to also perform time-of-flight measurements. The measurements could be one-way, if the transmission time and the reception time can be time-tagged with high accuracy, e.g. with atomic time references, or two-way, with the same ground station performing as transmitter and receiver. In any case, the ranging capability requires careful design of the signal structure and of the delays introduced by the signal paths and processing in the terminals. A properly designed optical ranging system should be able to measure time of flight well below one nanosecond, matching or improving on the capability provided by radiometric systems [19].

Optical wavelengths are not affected by the biggest contributor to X-band radiometric uncertainty, the delay created by charged particles. Charged particles in the ionosphere and in the interplanetary plasma create group delays and phase advances that are roughly proportional to the square of the wavelength, so they are negligible for optical frequencies. As for telemetry, time-of-flight measurements can be performed in daylight.

Methods for optical ranging has been demonstrated by a number of space missions [3,4,5,10], but have not yet been used for operational orbit determination.

IV. Case Studies

A number of interplanetary orbit determination scenarios have been analyzed to assess the suitability of optical tracking, and to compare its navigational performance with that achievable with radio frequency data [20,21]. The performance required by each mission depends on the accuracy with which the mission trajectory needs to be determined and predicted. Missions with more demanding requirements, such as a Mars landing mission, require a higher navigation performance than, for example, a drifting astrometry mission.

For each case, we simulate the relevant trajectories and sets of tracking data for different measurement types. We then assess applicable navigation performance metrics for different combinations of data types and assumptions. One of the objectives of our research is to determine how sensitive the navigation performance is to those assumptions, in order to focus efforts and development in those areas that can produce a greater payoff in terms of navigation performance, and to relax the performance requirements for those elements to which we are not sensitive.

We added to MONTE the capability to simulate optical-communications tracking using appropriate measurement models and scheduling constraints. The processing setup included the consideration of frame-tie errors, in order to model possible discrepancies between the Gaia frame and the ICRF, both at a global and a local scale. It also included other errors typically considered in this kind of analysis, such as media, earth orientation, station locations, star or quasar catalogue errors, planetary ephemeris, and spacecraft dynamical uncertainties.

The analyses performed in this study did not take into account the effect of weather on the availability of optical data. It was assumed that at all times a ground station with clear sky was available to perform the measurements. This could be accomplished by having multiple telescopes within the footprint of the returned laser signal, by performing redundant or dynamic scheduling of the tracking passes that takes into account local weather, and also by optimally siting the optical terminals.

A. Mars Lander Delivery

One of the most navigationally demanding scenarios is the delivery of a lander to the Mars atmospheric entry point, so it can safely land on the surface of the planet. Two metrics are important in this case: how precisely we deliver the spacecraft to the nominal target, and how well the spacecraft knows its state at entry—position and velocity—relative to a Mars-fixed frame. Delivery errors reduce the Entry, Descent and Landing safety margins by requiring the spacecraft to accommodate a wider range of entry conditions. Knowledge errors map into landed position errors, as there is no GPS on Mars, as the spacecraft needs to propagate its entry state using gyroscopes and accelerometers to actuate controls and land in the right place.

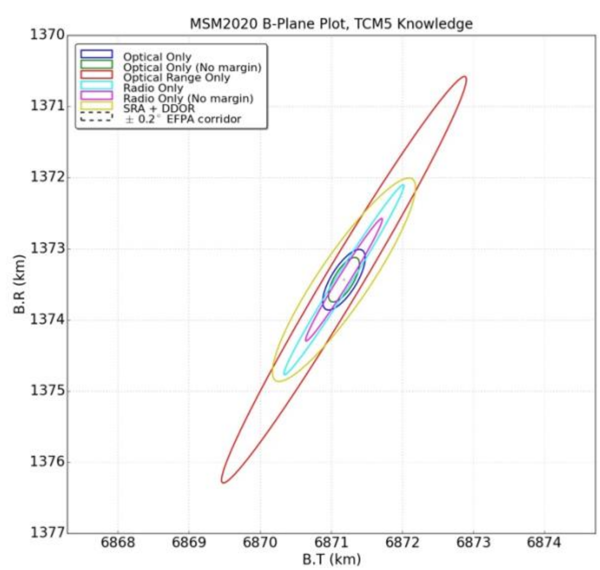

Fig. 4. Simulated Mars 2020 entry knowledge performance for selected data-type combinations (3-σ)

For our analysis, we simulated one of the possible interplanetary trajectories of NASA's next Mars rover mission, Mars 2020. This spacecraft is scheduled to launch in late summer 2020 and land in early spring 2021. The spacecraft is very similar to the Mars Science Laboratory, launched in 2011, for which we were able to perform very precise navigation, since it was a fairly dynamically quiet spacecraft [22].

The analysis compared the performance achievable with the X-band tracking data planned for Mars 2020 with that possible with different scenarios including optical data [20]. The variational and sensitivity analysis showed that the astrometry-only case was very poor—as expected—in the line-of-sight direction, similarly to what could be expected from a radiometric ΔDOR-only case. Adding ranging made the optical-only case perform as well as, or even better than, the radio-only case, because of the better line-of-sight accuracy and the more frequent plane-of-sky measurements. Varying the telescope size had a noticeable effect on the navigation performance, while the frame effects—at the level that they were being varied—had negligible impact, as did the level of optical range accuracy for this particular application.

B. Mars Orbiter

For this case, we used the orbit determination setup of NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission [23]. MAVEN is a spacecraft with a 4.6-hour orbital period, an inclination of 75º, and an eccentricity of about 0.47. It has a low periapsis in order to sample the upper levels of Mars' atmosphere.

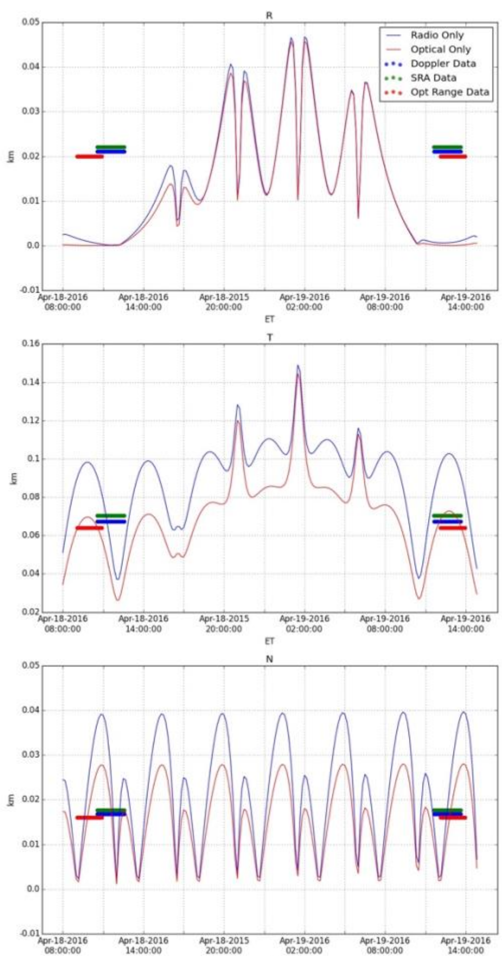

Fig. 5. Simulated MAVEN trajectory reconstruction performance in an RTN orbital frame with a Sun-Earth-Mars angle of 6º (1-σ).

The measurement simulation followed the tracking schedule used in operations, with eight-hour-long passes [21]. Some of these passes are performed using a low-gain antenna, since the high-gain antenna is body-fixed and cannot be pointed to the Earth when the spacecraft is collecting science data. In the optical case, this could be solved by using a gimballed optical terminal, but it highlights the issue that optical links could impose greater pointing constraints than radio links.

The performance metric that was compared in this scenario was the trajectory position error for reconstructed orbits. MAVEN requires trajectory reconstructions with better than 3-km accuracy. Orbit prediction errors are of course a function of the reconstructed orbit accuracy, but are dominated by errors in the prediction of the atmospheric density, that would affect both radio and optical in the same way. When similar tracking data schedules are used, optical outperformed radio during tracking passes, but during data gaps which data type is better seems to depend on the observing geometry. In any case, both cases are able to comply with the orbit reconstruction requirements. Modifying the optical range accuracy from 5 mm to 5 cm made little difference in the accuracy of the solution.

C. Asteroid Rendezvous

Another promising scenario for optical tracking is that of asteroid rendezvous missions. While high-accuracy optical astrometry is not possible for comets, it should be possible for asteroids using similar methods as those used for spacecraft enabling a precise measurement of the position of the spacecraft with respect to the asteroid. The analysis setup used for this scenario mimics that used to analyze possible future missions to visit asteroids, and compares the results obtained using different combinations of ground-based radiometric data, ground-based

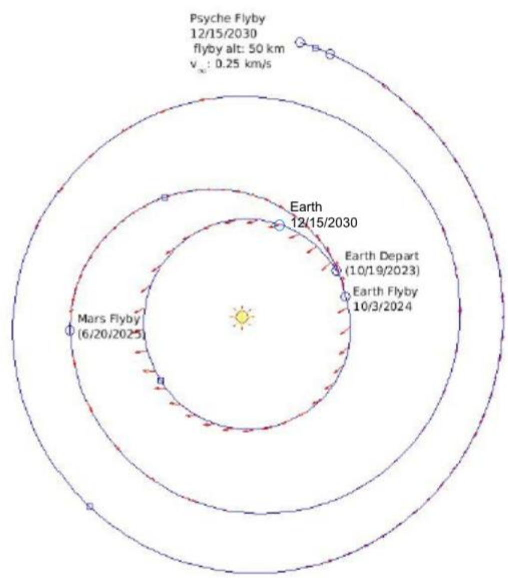

Fig. 6. Simulated Trajectory for the Psyche scenario

optical data and on-board optical imaging. The performance metrics that are used are the delivery errors after the last maneuver before the flyby, expressed in B-plane coordinates.

The case presented here is a mission to 16 Psyche. 16 Psyche is a main-belt metallic asteroid with a 250-km mean diameter. The flyby for this case is assumed to happen at an altitude of 50 km at 0.25 km/s on December 15, 2030. The trajectory was designed to allow for a flyby with near-optimal ground observing conditions. While the simulated mission used solar-electric propulsion, we assumed that there was a forced coast for 28 days before the flyby, and used a 10-week arc of data, with the last maneuver five days before the flyby. We used a measurement weight for astrometric observations of 1 miliarcsecond and an optical range weight of 5 cm. In addition to the spacecraft state, we estimated once-per-day attitude desaturations, and impulse burns leading up to the flyby, as well as the asteroid ephemeris and mass. The trajectory was designed so that 16 Psyche and the Earth would be in the same side of the Sun on the period leading to the flyby, allowing for astrometric near-optimal observability.

Table 1 shows the cases that we analyzed in this scenario, and the resulting performance metrics. Performing Gaia-enabled high-precision ground astrometry of the asteroid improves the linearized time of flight (LTOF) performance of the radio case. The last three cases, with different combinations of optical tracking, produce similar results. In a scenario like this, we could use an on-board optical system optimized for terminal navigation and we could perform distant navigation using only ground-based optical tracking.

Table 1. Psyche flyby delivery results

Case	**B-plane ellipse (km, 1-σ)**	**LTOF (sec, 1-σ)**
Radio + on-board optical	2.0 × 1.9	112
Radio + on-board optical + asteroid obs.	2.0 × 1.9	18
Optical, ground + on-board	2.0 × 1.9	25
Optical + asteroid observations	2.0 × 1.9	17
Ground optical only, including asteroid obs.	2.4 × 2.0	19

We also run variations on the range weight and astrometry accuracy, and observed that the LTOF results were very sensitive to the astrometry quality—i.e. telescope size—but not sensitive to the range weight for the 5 mm and 5 cm values that were analyzed.

CONCLUSION

Ground-based optical tracking can replace radio-frequency tracking under the appropriate conditions. After the release of the final Gaia catalog, if a geographically diversified network of telescopes is available, optical tracking could replace radio tracking for a number of deep-space mission scenarios.

A telescope with a diameter of around 5 m may be able provide plane-of-sky accuracies competitive with ΔDOR. Range accuracies of about 5 cm seem to be sufficient for navigation applications, while higher accuracies could enable new scientific investigations.

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